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FEASIBILITY OF PERMANENT MAGNET DESIGN FOR HIGH POWER MICROWAVE GENERATOR

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PHILLIPS LABORATORY
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13. ABSTRACT ***(Maximum 200 Words)***
The feasibility of designing a permanent magnetic field system for the Phillips Laboratory Relativistic Klystron Oscillator (RKO) was investigated. It was determined that it is nearly possible to obtain the desired 0.5 T magnetic field within the size and geometry configuration constraints. However, whereas the current RKO design requires a uniform field for a 60 cm length, the permanent magnet design will provide a uniform field for 52 cm. The existing RKO magnet system has a weight of about 600 kg for the magnet, plus an additional 1500 kg for the laboratory power supply currently in use. The design weight for the permanent magnet presented here is about 800 kg total. A simpler, straight solenoid system was only briefly considered. Modest magnet improvements of a few percent may be expected in the next few years but large scale improvements are not expected.

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1. INTRODUCTION

The Phillips Laboratory (PL) has conducted extensive research on the Relativistic Klystron Amplifier/Oscillator (RKA/RKO) for the past several years.[1,2] This device has demonstrated a capability of exceeding 1 GW peak power with the energy per pulse equal to 170 joules.. The radiation frequency of this narrow band tube as tested at PL is in the L-band (1 - 2 GHz). Such a powerful microwave source has the potential for use in a range of Air Force applications. However, the laboratory system is bulky, heavy, and requires large amounts of supplied power.

One of the components of a high power source like the RKA/RKO is the magnet and its associated equipment. Unfortunately, this subsystem is very bulky, heavy, and currently requires a lot of power to energize. To make an electron beam source like the RKA a viable High Power Microwave (HPM) source for use on board aircraft (large and small) ways must be sought to reduce the total weight, footprint, and power requirements.

The laboratory RKA/RKO has used an electromagnet to contain the electron beam in its cavities. This magnet, with its power supply, weighs 4,700 lb, requires a volume of 23 m^3 and 86 kJ of electrical energy for a typical shot. This amounts to 4300% of the extracted beam energy! The electromagnet produces the required field on the beam axis of about 500 G (0.5 Tesla). Clearly, economy of weight and energy can be achieved by seeking alternate magnetic field solutions.

2. APPROACH

This paper reports on a feasibility study to investigate the latest permanent magnet technologies in the U. S. and abroad. Permanent magnets will have the obvious advantage of not requiring an external power source, and may be less bulky and massive. The question

[1] Hendricks, K., et al., "Development of an Annular Electron Beam HPM Amplifier," PL-TR-94-1065, September, 1994.

[2] Hendricks, K., et al., Phys. Rev. Lett., 76, 1, 154-157 (1996).

addressed in this study is whether any permanent magnet material can be used to sustain a high enough field over the volume required for the present RKA/RKO design.

The Phillips Laboratory Relativistic Klystron Oscillator (RKO) is shown in Fig. 1. After consultation with Dr. Kyle Hendricks of the PL, it was decided that the two cavities could be moved to the extreme radius in order to simplify the design. This resulted in a magnet configuration as shown in Fig. 2. The shaded area in this figure shows where magnetic material may be located, not the details of the orientation of the magnet building blocks. Figure 3 shows a simplified geometry which may be of interest to, for instance, Backward Wave Oscillators. This was intended as a "fall-back" case if the geometry in Fig. 2 could not produce the desired field strength.

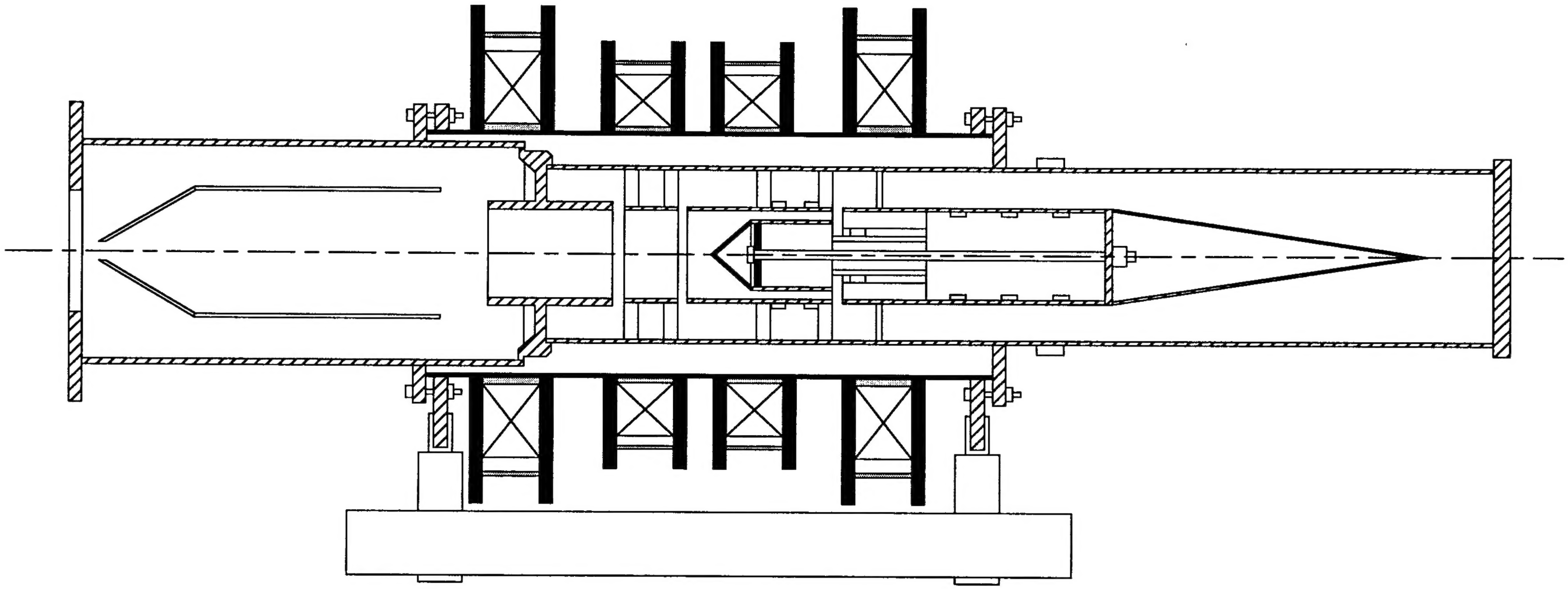
In the initial part of the study, we benefited from helpful discussions with Dr. E. Potenziani and H. Leupold from the US Army Research Laboratory, Physical Sciences Directorate, Ft. Monmouth, NJ. In the actual design, we worked with Professor A. Ye. Yermakov, Head of the Applied Magnetism Laboratory, Institute for Metal Physics, Ural Branch of the Russian Academy of Sciences in Ekaterinburg, Russia. Their computer codes were used in the final design.

Several US manufactures and distributors of permanent magnets were contacted regarding their products. The relatively low level of interest shown by these companies was somewhat surprising. The important parameters for defining permanent magnets are the following. Note that in the region (quadrant) of interest, H is negative but the minus sign is usually suppressed.

H_{ci} - Intrinsic coercivity
(where the magnetization changes sign)

H_c - Coercivity
(the value of H which makes the flux density, B, go to zero)

B_r - remanence
(the value of B when the magnetizing force, H, is zero)



Beam Parameters
V_{beam} = 500 kV
I_{beam} = 10 kA
τ =300 nsec
B_2 = 5-8 kG
$P_{magnetron}$ = 500 kW

Beam Dimensions
$r_{beamline}$ = 7.65 cm
r_{inner} = 6.6 cm
r_{outer} = 7.1 cm
Cavity Dimensions
z_{gap} <= 2 cm
r_{max} = 14.6 cm
r_{min} = 8.6 cm
z_{vane} = 11.0 cm

Measured Voltages on Rf gaps
$V_1 \sim$ 150 kV
$V_2 \sim$ 220 kV
$V_{ext} \sim$ 350 - 500 kV

Fig. 1. 2 Cavity RKO with Center Conductor Extractor

$r_1 = 5.0$
$r_2 = 7.65$
$r_3 = 13.64$
$r_4 = 16.86$
$r_5 = 22.86$

ℓ_1 and ℓ_2 - not critical but as short as possible

All dimensions in centimeters

Cross hatched areas indicate regions where magnetic material may be places

Seeking maximum B_2 between r_1 and r_2

Fig. 2. HPM Permanent Magnet Space Availability

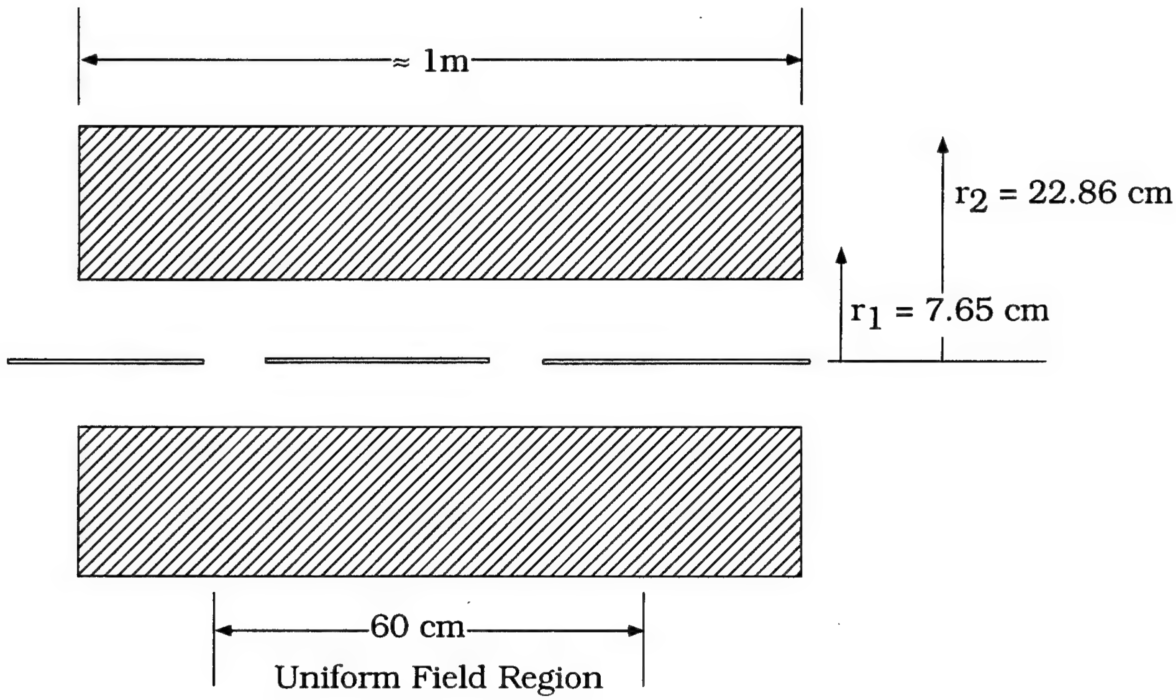


Fig. 3. Simplified Magnet Geometry

$(BH)_{max}$ - the maximum value of the BH product. Operating at this point gives the smallest magnet material volume

The "best" material we were able to find is manufactured by VACUUMSCHMELZE GmBH in Germany under the name VACODYM 510 HR and sold in the US by Magnet Sales and Manufacturing, Inc., Culver City, CA, under the name of "Grade No. 48". This material is advertised with the following parameters.

H_{ci} =	13,500 Gauss (1.35 T)
H_c =	12,900 Gauss (1.29 T)
B_r =	14,100 Gauss (1.41 T)
$(BH)_{max}$ =	48 MGOe (385 kJ/m^3)

These parameters are defined in Fig. 4 for an idealized material. For this idealized material, it can be shown that - $(BH)_{max} = \mu_o (M_{sat}/2)^2$ when $|H_{ci}| > M_{sat}/2$. Remember that for "soft" magnetic materials, which retain no magnetization ($M_r = 0$),

$$B = \mu_o (1 + \chi) H + \mu_o\mu_r H,$$

whereas for permanent magnets

$$B = \mu_o [(1 + \chi) H + M_r],$$ where χ is the susceptibility.

This material (Grade 48), which is an isostatically pressed Nd-Fe-B alloy, sells for about \$165/kg in the quantities of interest for the magnets considered in this report. Our Russian colleagues as well as some magnet experts in the US expressed some surprise over these performance parameters but the manufacturer has an overall excellent reputation. The distributor tells us that, although the samples so far has tested out near B_r = 1.38 T rather than B_r = 1.41 T, the quality is steadily improving. The manufacturer states in their sales literature that their goal is $(BH)_{max}$ = 50 MGOe (400 kJ/m^3). In the calculations made with the Russian design code, we chose for simplicity, to use B_r = 1.0 T with the understanding that we can scale these results by the actual remanence.

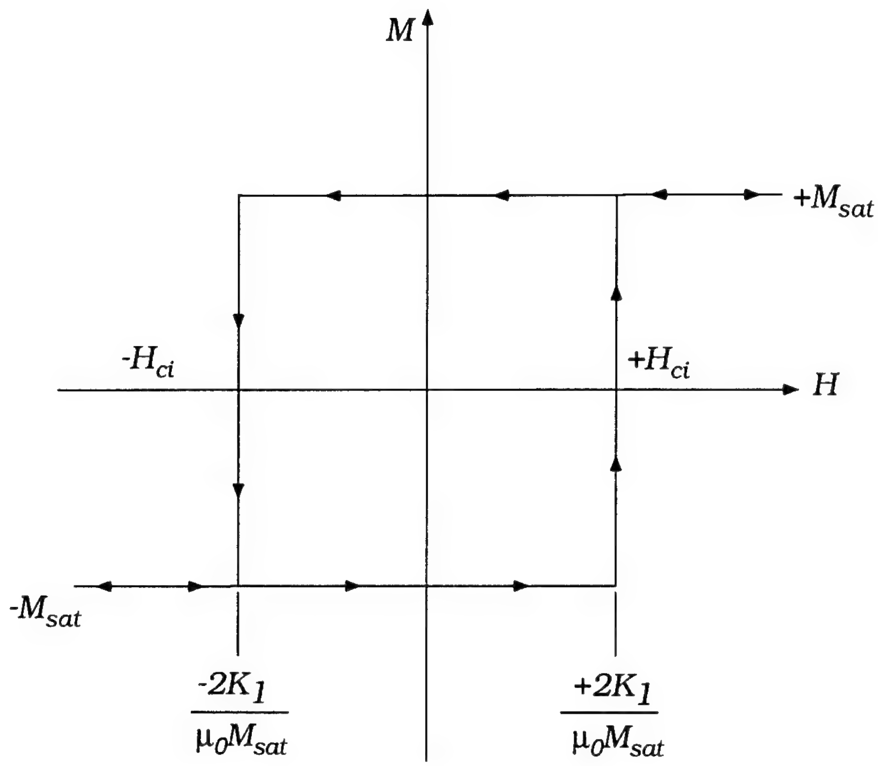


Fig. 4a. Intrinsic magnetization characteristic for an elemental volume of a magnet (from P. Campbell, "Permanent Magnet Materials and their Applications," Cambridge Univ. Press, 1994)

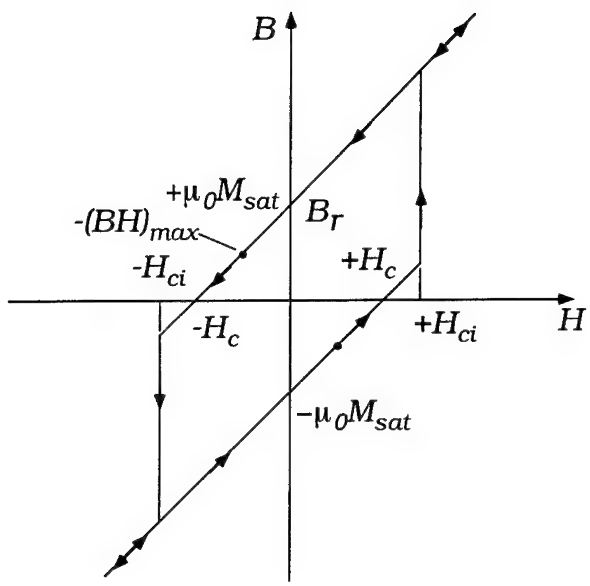


Fig. 4b. B versus H characteristic for a magnet (from P. Campbell, "Permanent Magnet Materials and their Applications," Cambridge Univ. Press , 1994)

Note that all types of rare earth magnets are susceptible to oxidation which can cause permanent metallurgical changes. These magnets must therefore be encapsulated or plated, e.g. with a ~ 10 μm aluminum or cadmium chromate plating. The magnets are also susceptible to mechanical pressure and shocks (i.e. do not drop them since they are also somewhat fragile). Thermal fluctuations can also cause irreversible changes but this can be reduced by cycling the magnet several times through a slightly larger temperature variation that its expected range. At the Curie temperature complete demagnetization will occur. For the magnet material discussed here, this is 310°C but the magnet should not be operated above 80°C. The magnet has a temperature coefficient of - 0.11% $\Delta B_r/B_r$/°C so it would be advisable to keep its temperature relatively constant. Samarium-Cobalt (SmCo) magnets have a temperature coefficient of only - 0.03% and a maximum operating temperature as high as 350°C but the other parameters, defined earlier, are not as high (e.g. B_r = 11,600 Gauss (1.16 T)). It has been difficult to find information about the radiation sensitivity of the Nd FeB magnets. The consensus opinion seems to be that they are relatively insensitive to x-rays but that the epoxy or "glue" used in the magnet assembly may be somewhat influenced. This may need some further investigation. Direct particle (proton) beam interaction has shown NdFeB samples to lose 50% of their magnetization at a dose of 4×10^6 rads. (Ref. Magnet Sales and Manufacturing brochure, 1995, p ix).

3. Magnet Design

1. Simple Solenoid Design

For the simplified geometry shown in Fig. 3, we only did a quick calculation and did not optimize anything. The actual field components at r = 7.15 cm is shown in Fig. 5 along with the orientation of the various magnet "building blocks". In all the designs with the Russian codes we assumed a remanent magnetism of B_r = 1.0 Tesla. For this case, we got a central B_z = 0.4 T which scales to B_z = 0.56 T for the Grade 48 material described earlier. The field ripple shown on this curve can be reduced by further magnet optimization and the use of soft magnetic materials in appropriate positions. No effort was made to do this.

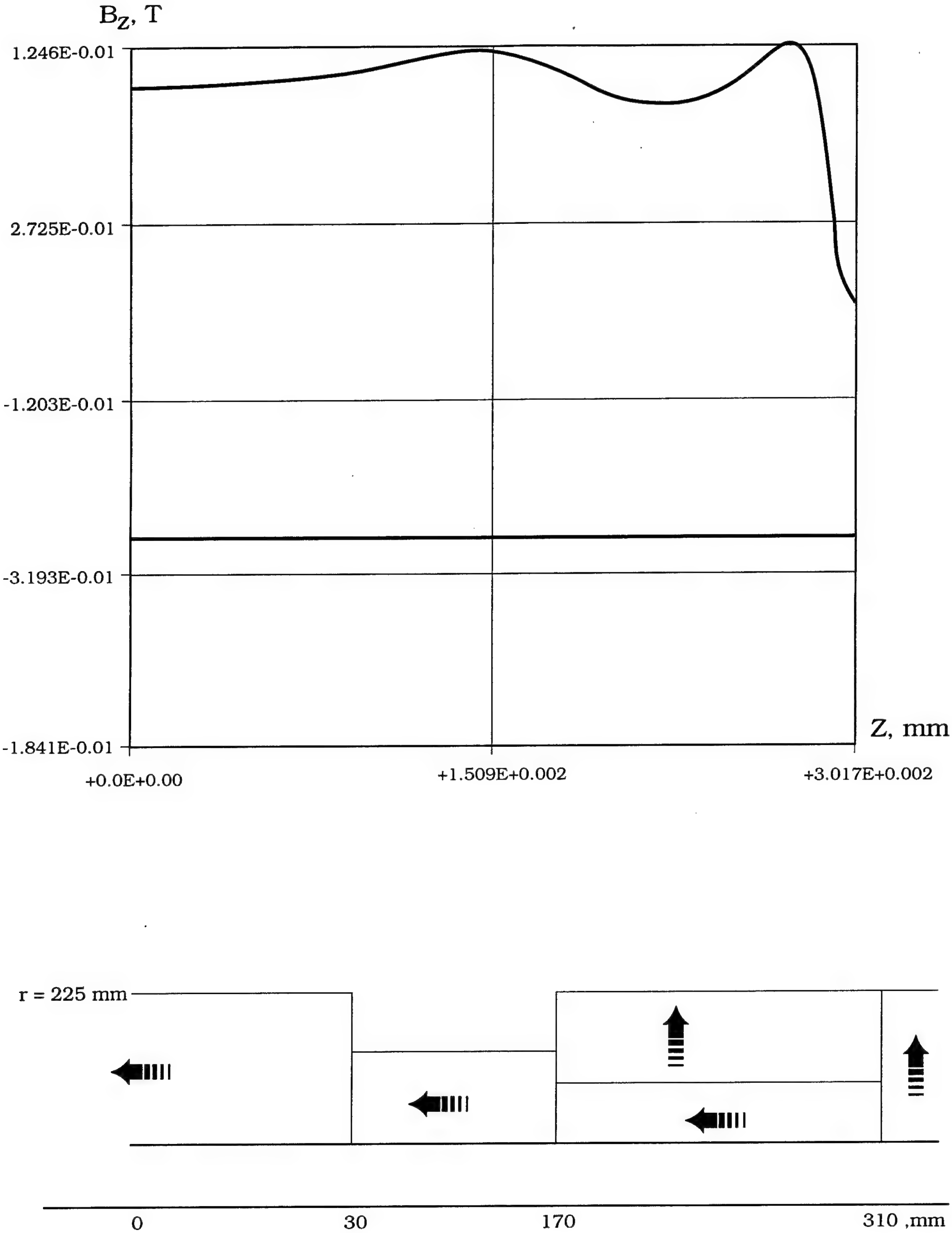


Fig. 5. Magnet Design for Simple Solenoid

In a simple analytical analysis for a 70 cm uniform field region, Dr. H. Leupold of the US Army Research Laboratory got $B_z = 0.49$ T for $B_r = 1.3$ T which scales to $B_z = 0.53$ T for $B_r = 1.4$ T. He did not calculate any actual field profile, however, since this would take a finite element analysis. In the work with the Russians, trying various parameter variations, we found that the B_z field for this geometry scales much faster than inverse linear with length, - actually more like exponential. At a uniform field region of 70 cm the more detailed Russian calculations only gave $B_z = 0.42$ T at $B_r = 1.4$T.

The possibility of using a hybrid magnet system (permanent plus electro magnets) was considered briefly. This would probably involve making axial slots in the magnets, unless the current rise time is very slow, since the NdFeB magnets have fairly high conductivity. This is, however not a simple task because of the required support structure to hold the magnets together.

Another possibility is to use periodic magnet structures with field reversals. See Fig. 6 for an example. Dr. Hendricks was not sure how this would affect the RKO operation but it has been used with great success in conventional TWT's. Even the case of using only one field reversal can increase the field by maybe as much as 20%. An example will be shown for the RKO case discussed next.

2. Relativistic Klystron Oscillator Magnet Design

The RKO configuration and the space allotted for magnet structure was shown in Figs. 1 and 2. Figure 7 shows the present field configuration with the pulsed coil magnet system. This system is, of course, limited in repetition rate by the charging power supply and eventually by coil cooling, which motivated the present study.

Figure 8 shows the locations and polarities of the magnet sub-building blocks, consistent with the space made available and shown in Fig. 2. The magnet material weighs about 600 kg plus about 200 kg of support structure. For calculation purpose and ease in scaling to other materials a remanence of $B_r = 1.0$ T was chosen for the field calculations. Figure 9 shows the axial and radial fields ($B_z(z)$ and $B_r(z)$) at r = 7 cm and Figure 10 shows

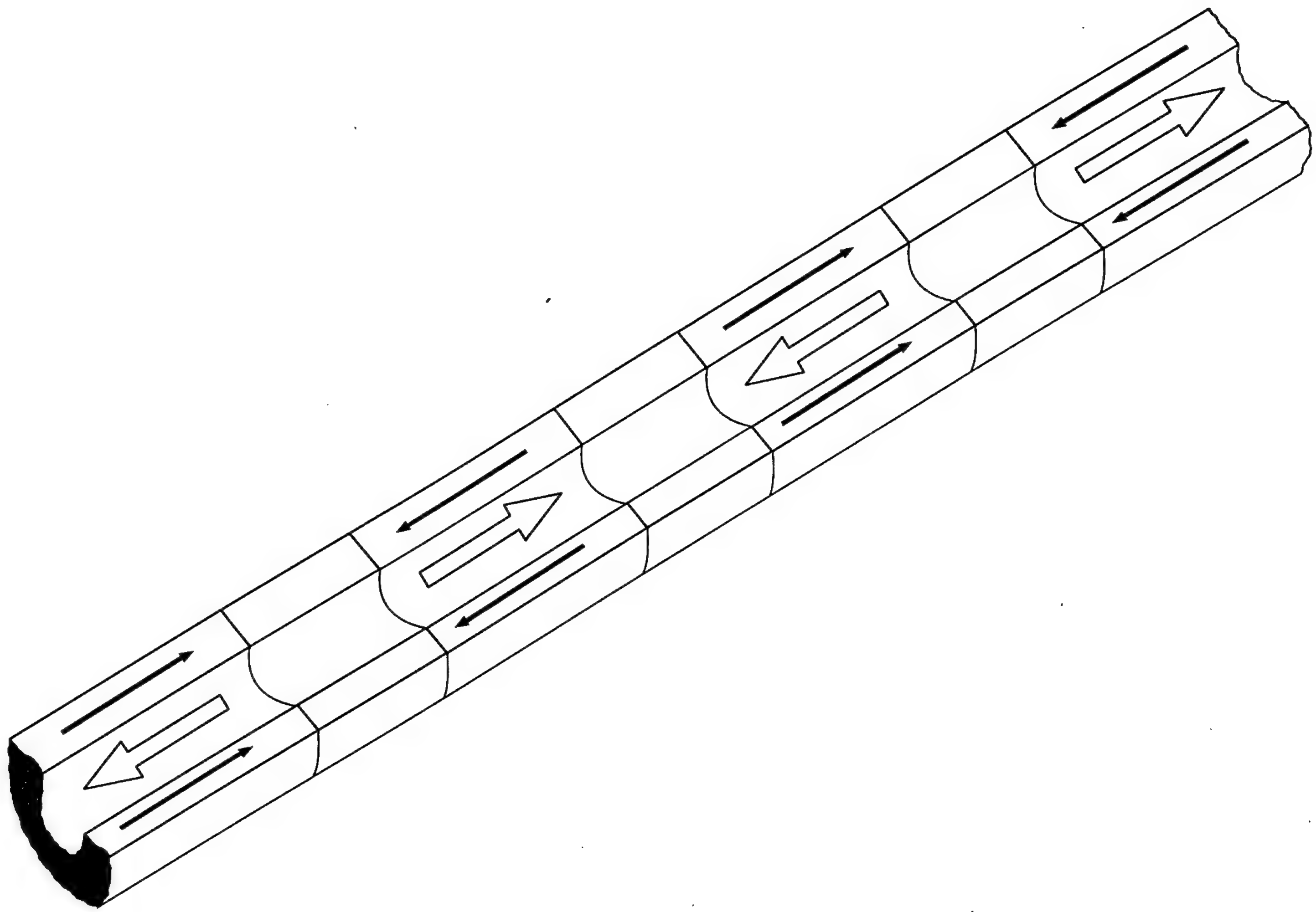


Fig. 6. Solenoid Field with Reversals

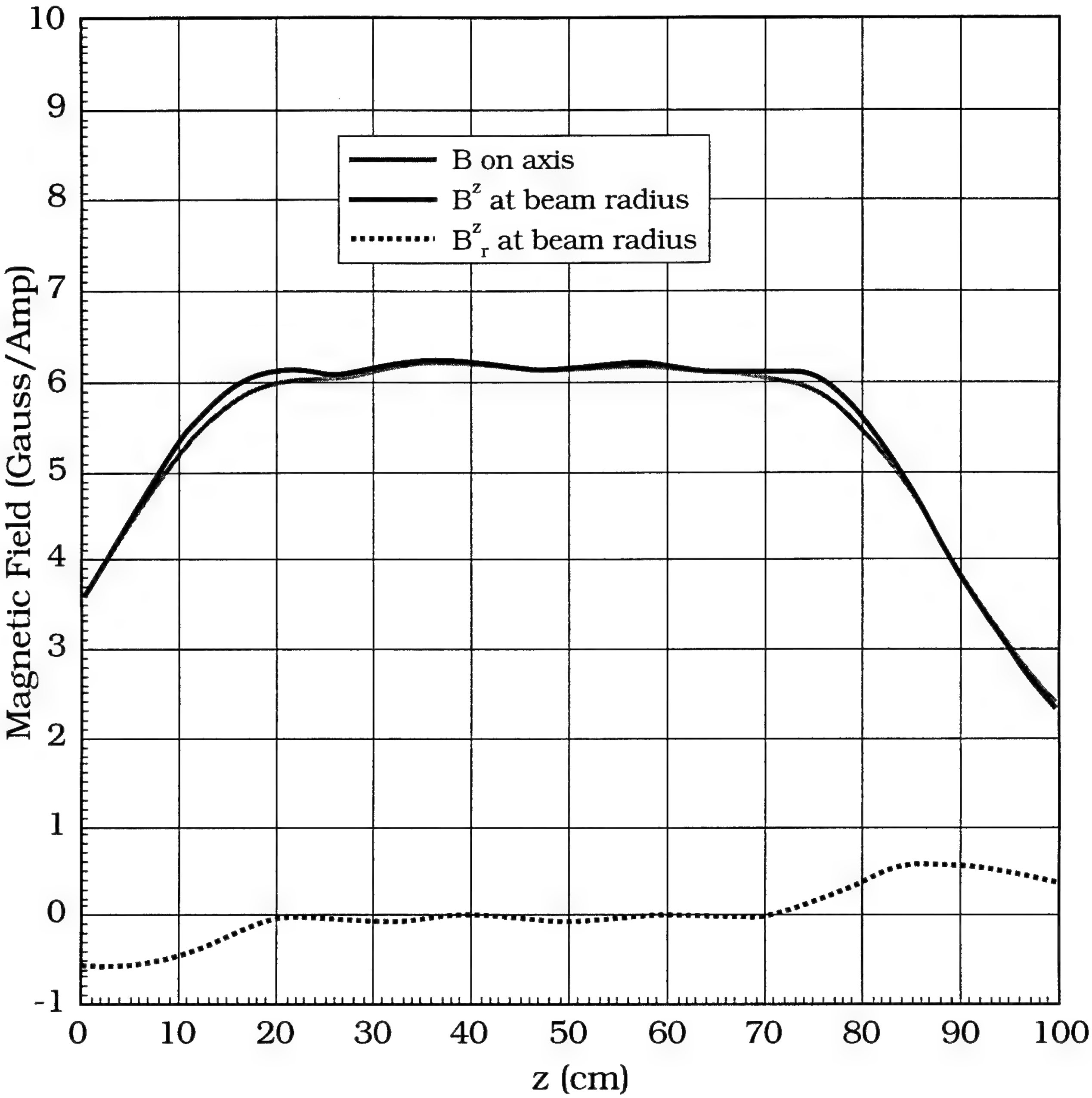


Fig. 7. Present B-field Profiles with Electromagnets.

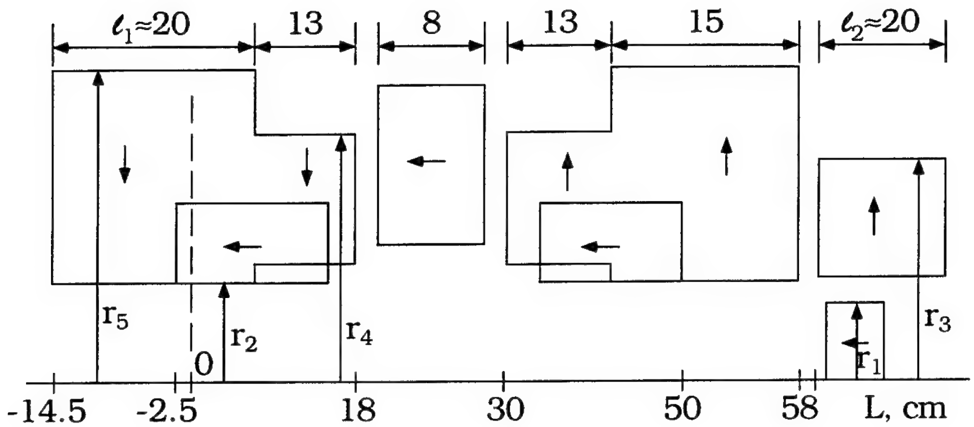


Fig. 8. Magnet Structure for RKO
(All dimensions in cm)

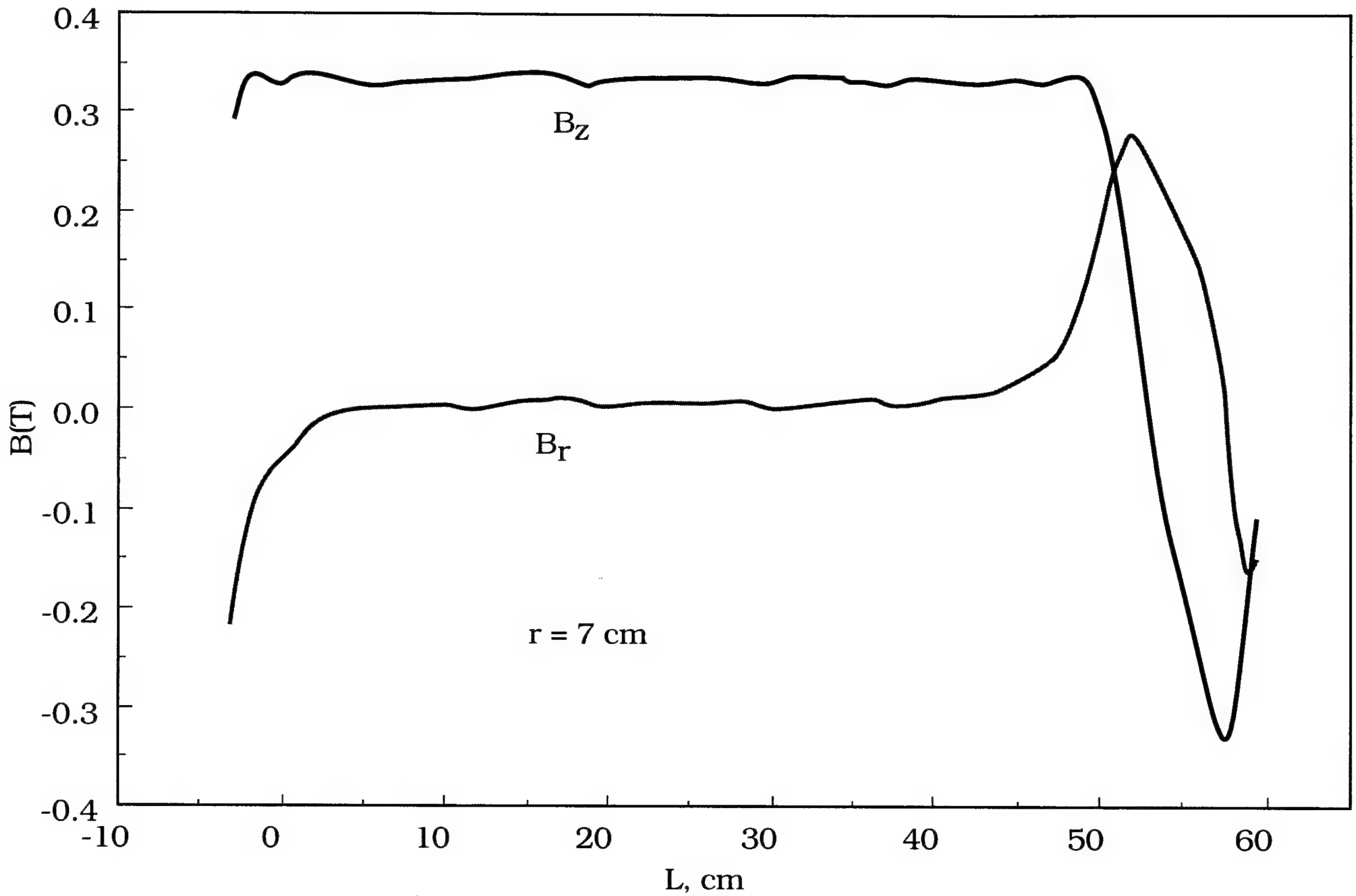


Fig. 9. Axial and Radial Magnetic Fields at r = 7 cm

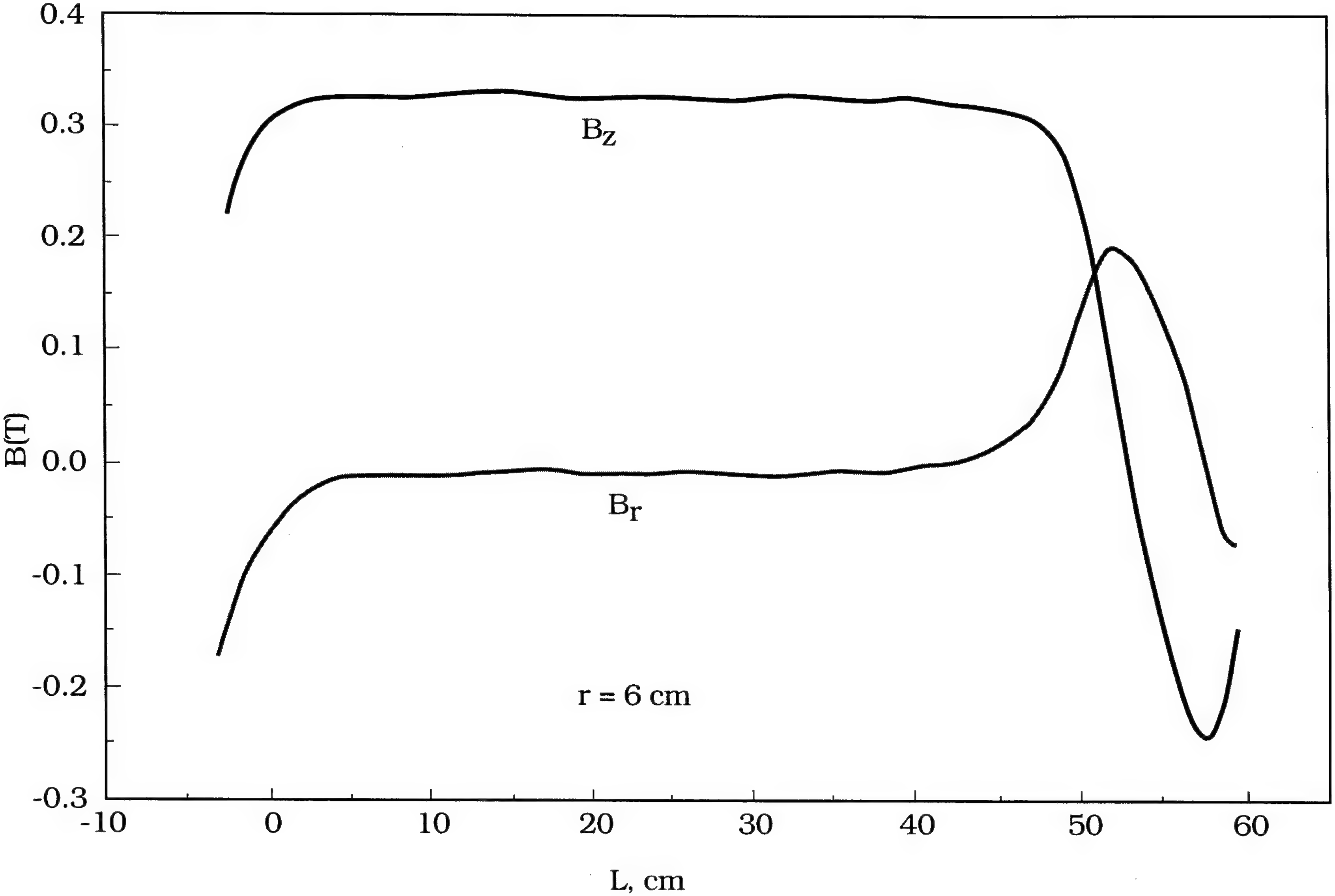


Fig. 10. Axial and Radial Magnetic Fields at r = 6 cm

the same at r = 6 cm. The field uniformity is about ± 1.9% but this can be improved by further detailed optimization and use of soft magnetic materials.

Note, however, that the uniformity region is only 52 cm rather that the desired 60 cm. The uniformity region can be extended by extending ℓ_1 in Fig. 7, whereas extending ℓ_z does not help much due to its smaller radius . The uniform field value of $B_z \sim 0.333$ T scales to about 0.47 T using the Grade 48 material described earlier. This is close enough to the desired 0.5T that one may expect to achieve this value by final optimization and "fine tuning".

4. Conclusions

This study indicates that it is possible to obtain high density (~ 0.5 T) uniform B_z fields in relatively large diameter (> 15 cm) systems using currently available permanent magnets. The cases discussed underwent a modest optimization procedure but further improvements of maybe 10% can be reasonably expected. Also, a modest increase of a few percent (< 5%) in magnetic materials may be expected by evolutionary procedures. Nothing revolutionary is expected in the near future (~ 5 years). The new MURI program on magnetic materials should be closely watched, however. This program may have the greatest potential for significant material advances. The ± 1.9% field uniformity reached in our calculations can almost certainly be improved to less than ± 0.5% by use of soft magnetic materials and final magnet tuning. The possible use of field reversed systems should be examined for each specific case (BWO, RKO, etc.) using a PIC code, since this can provide significant field enhancement. In our case it provided a 20% increase using only one field reversal.

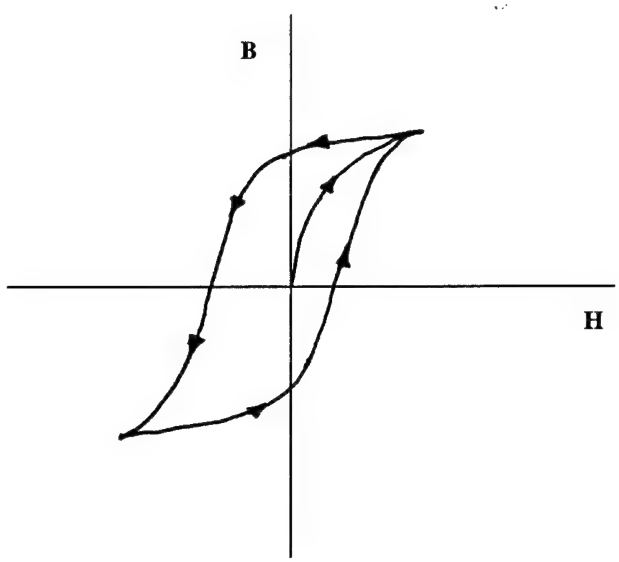
The RKO system weighs about 800 kg (1760 lbs) (600 kg magnet material plus 200 kg support structure). The magnet material itself (no assembly) will cost about $130,000 since about 800 kg of magnet material must be used due to losses in cutting the samples to proper size (a reduced cost may be expected in the future if this material finds wide application). The weight of a repetitive, pulsed, cooled, electromagnetic coil system is expected to weigh much more than 800 kg. The present single shot, uncooled, system weighs

about 2136 kg (4700 lbs) according to Dr. Hendricks. An estimate of the weight and cost of a repetitive, optimized, system is beyond the scope of this investigation.

APPENDIX

Magnet Fundamentals[3]

The basis of magnet design is the B-H curve, or hysteresis loop, which characterizes each magnet material. This curve describes the cycling of a magnet in a closed circuit as it is brought to saturation, demagnetized, saturated in the opposite direction, and then demagnetized again under the influence of an external magnetic field.

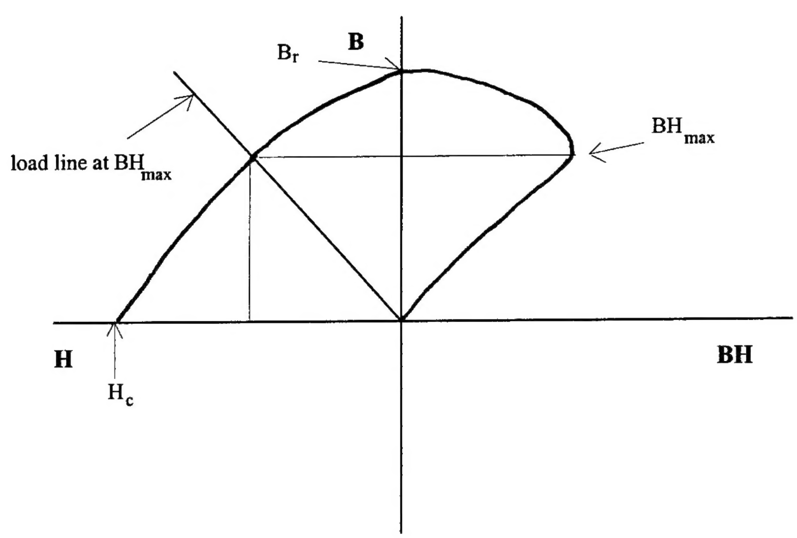


Hysteresis Loop

The second quadrant of the B-H curve, commonly referred to as the "Demagnetization Curve", describes the conditions under which permanent magnets are used in practice. A permanent magnet will have a unique, static operating point if air-gap dimensions are fixed and if any adjacent fields are held constant. Otherwise, the operating point will move about the demagnetization curve, the manner of which must be accounted for in the design of the device.

[3] For example, see sales brochure by Magnet Sales & Manufacturing, Inc., undated)

The three most important characteristics of the B-H curve are the points at which it intersects the B and H axes (at B_r - the residual induction - and H_c - the coercive force - respectively), and the point at which the product of B and H are at a maximum (BH_{max} - the maximum energy product). **B_r** represents the maximum flux the magnet is able to produce under closed circuit conditions. In actual useful operation permanent magnets can only approach this point. **H_c** represents the point at which the magnet becomes demagnetized under the influence of an externally applied magnetic field. **BH_{max}** represents the point at which the product of B and H, and the energy density of the magnetic field into the air gap surrounding the magnet, is at a maximum. The higher this product, the smaller need be the volume of the magnet. Designs should also account for the variation of the B-H curve with temperature.



The Demagnetization Curve

When plotting a B-H curve, the value of B is obtained by measuring the total flux in the magnet (Φ) and then dividing this by the magnet pole area (A) to obtain the flux density ($B= \Phi/A$). The total flux is composed of the flux produced in the magnet by the magnetizing field (H), and the intrinsic ability of the magnet material to produce more flux due to the orientation of the domains. The flux density of the magnet is therefore composed of two

magnetic materials to produce flux. The intrinsic flux density is given the symbol B_i where total flux $B = H + B_i$, or, $B_i = B - H$. In normal operating conditions, no external magnetizing field is present, and the magnet operates in the second quadrant, where H has a negative value. Although strictly negative, H is usually referred to as a positive number, and therefore, in normal practice, $B_i = B + H$. It is possible to plot an intrinsic as well as a normal B-H curve. The point at which the intrinsic curve crosses the H axis is the intrinsic coercive force, and is given the symbol H_{ci}. High H_{ci} values are an indicator of inherent stability of the magnet material. The normal curve can be derived from the intrinsic curve and vice versa. In practice, if a magnet is operated in a static manner with no external fields present, the normal curve is sufficient for design purposes. When external fields are present, the normal and intrinsic curves are used to determine the changes in the intrinsic properties of the material.

UNITS OF MEASURE

The systems of units of measure are common: the cgs (centimeter, gram, second), SI (meter, kilogram, second), and English (inch, pound, second) systems.

Unit of Measure Systems

Unit	Symbol	cgs System	SI System	English System
Flux	Φ	Maxwell	Weber	Maxwell
Flux Density	B	Gauss	Tesla	lines/in^2
Magnetomotive Force	F	Gilbert	ampere turn	ampere turn
Magnetizing Force	H	Oersted	ampere turns/m	ampere turns/in
Length	L	cm	m	in
Permeability of a vacuum	μ_o	1	$0.4\pi \times 10^{-6}$	3.192

Conversion Factors

Multiply	by	To obtain
inches	2.54	centimeters
lines/in^2	0.155	Gauss
lines/in^2	1.55×10^{-5}	Tesla
Gauss	6.45	lines/in^2
Gauss	10^{-4}	Tesla
Gilberts	0.79577	ampere turns
Oersteds	79.577	ampere turns/m
Ampere turns	0.4π	Gilberts
Ampere turns/in	0.495	Oersteds
Ampere turns/in	39.37	Ampere turns/m

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